

**US Army Corps
of Engineers**Construction Engineering
Research Laboratories

(2)

An Evaluation of Reed Bed Technology To Dewater Army Wastewater Treatment Plant Sludge

by

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93-29834

As operator of over 100 small wastewater treatment plants (WWTPs), the Army has an interest in efficient and cost-effective sludge dewatering systems. Many Army wastewater treatment plants use conventional sand-drying beds to dewater sludge. However, sand drying involves costly regular removal of sludge, and sand-drying beds are vulnerable to operational problems with long drying periods during wet weather and sand media clogging.

Successful new technologies for sludge treatment in small-scale WWTPs include wedgewater beds, vacuum-assisted beds, and reed-bed systems. This study builds on a previous USACERL evaluation of wedgewater and vacuum-assisted bed performance by compiling operational data from municipal and industrial WWTPs that have reed bed systems to evaluate their potential for Army use. The use of reeds speeds sludge dewatering because the root systems maintain natural drainage channels throughout the sludge volume, and because reeds complement air drying by drawing water into the plant for evapotranspiration. Reed beds were found to be easier to operate and maintain than sand-drying beds, and to virtually eliminate the need for regular sludge removal. Moreover, reed beds can be simply and efficiently retrofit to existing sand-drying beds. Because the Army has large-area drying beds that can be converted to reed beds economically, reed bed systems were found to have a good potential for use at Army WWTPs.

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE September 1993	3. REPORT TYPE AND DATES COVERED Final		
4. TITLE AND SUBTITLE An Evaluation of Reed Bed Technology To Dewater Army Wastewater Treatment Plant Sludge		5. FUNDING NUMBERS 4A162720 A896 TB2		
6. AUTHOR(S) Byung J. Kim, Raul R. Cardenas, and Satya P. Chennupati				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Construction Engineering Research Laboratories (USACERL) P.O. Box 9005 Champaign, IL 61826-9005		8. PERFORMING ORGANIZATION REPORT NUMBER TR-EP-93/09		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Center for Public Works (USACPW) ATTN: CECPW-FU-S Bldg. 358 Fort Belvoir, VA 22060-5516		10. SPONSORING/MONITORING AGENCY REPORT NUMBER		
11. SUPPLEMENTARY NOTES Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) As operator of over 100 small wastewater treatment plants (WWTPs), the Army has an interest in efficient and cost-effective sludge dewatering systems. Many Army wastewater treatment plants use conventional sand-drying beds to dewater sludge. However, sand drying involves costly regular removal of sludge, and sand-drying beds are vulnerable to operational problems with long drying periods during wet weather and sand media clogging. Successful new technologies for sludge treatment in small-scale WWTPs include wedgewater beds, vacuum-assisted beds, and reed-bed systems. This study builds on a previous USACERL evaluation of wedgewater and vacuum-assisted bed performance by compiling operational data from municipal and industrial WWTPs that have reed bed systems to evaluate their potential for Army use. The use of reeds speeds sludge dewatering because the root systems maintain natural drainage channels throughout the sludge volume, and because reeds complement air drying by drawing water into the plant for evapotranspiration. Reed beds were found to be easier to operate and maintain than sand-drying beds, and to virtually eliminate the need for regular sludge removal. Moreover, reed beds can be simply and efficiently retrofit to existing sand-drying beds. Because the Army has large-area drying beds that can be converted to reed beds economically, reed bed systems were found to have a good potential for use at Army WWTPs.				
14. SUBJECT TERMS wastewater treatment plant sludge dewatering systems reed bed technology			15. NUMBER OF PAGES 44	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT SAR	

FOREWORD

This research was conducted for the U.S. Army Center for Public Works (USACPW), Fort Belvoir, VA, under Project 4A162720A896, "Environmental Quality Technology"; Work Unit TB2, "Appropriate Technology for Army Anaerobic Digester Sludge." The technical monitor was Malcolm McLeod, CECPW-FU-S.

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AN EVALUATION OF REED BED TECHNOLOGY TO DEWATER ARMY WASTEWATER TREATMENT PLANT SLUDGE

1 INTRODUCTION

Background

In terms of operations, costs, and processing, the management and handling of wastewater sludge makes up a significant part of Army wastewater treatment. Over the years, a variety of sludge management technologies have become available. An installation may choose to dewater sludge by mechanical or natural methods based on the size of its dewatering facilities, on land availability, or on the nature of the sludge. Most U.S. Army installations practice anaerobic digestion for sludge stabilization, followed by the use of conventional sand-drying beds for sludge dewatering.

Small wastewater treatment plants, especially Army plants, commonly use sand-drying beds to dewater sludge for their many advantages: they are simple in design; easy to operate; low-maintenance; energy-efficient; and relatively inexpensive to construct, operate, and maintain. With these systems, the sludge is simply spread over the sand-drying beds and dewatered by a combination of evaporation and drainage.

However, sand-drying beds require long dewatering times (3 to 4 weeks), and need regular, intensive manual labor to remove the dewatered sludge. Sand-drying beds are also vulnerable to bad weather conditions and sometimes experience operational problems related to clogging of both the media and underdrains.

The U.S. Army Construction Engineering Laboratories (USACERL) has been investigating improved ways to dewater sludge. Two alternatives to sand-drying identified in this effort were the use of wedgewater beds and reed beds. A USACERL study found that wedgewater beds were most effective where space is critically limited (Kim et al. 1992).

"Reed bed dewatering" is a relatively new modification to sand-drying beds that uses the common reed (genus *Phragmites*) to treat wastewater sludges. The reed bed process was first used to treat wastewater (Haider 1985), and only later to dewater sludge. In this process, wastewater treatment plant sludges are applied to an actively growing stand of common reeds under controlled conditions. The growing reeds derive moisture and nutrients from the sludge; over time, the rooted plants and their root ecosystem, combined with the effects of weathering, dewater the sludge and improve its characteristics. As in sand-drying beds, the sludge dries naturally, by evaporation and drainage. Reed bed technology has been successfully demonstrated in the northeastern United States in sludge dewatering (U.S. Environmental Protection Agency [USEPA] September 1987), and more than 50 existing reed beds are currently in operation. This study surveyed technical information on the use of reed bed technology to establish the baseline for using this relatively new alternative technology at U.S. Army wastewater treatment plants.

Objectives

The objectives of this study were to: (1) compile and evaluate technical information on the use of reed beds to dewater wastewater treatment plant sludges in the United States, (2) compare the use of reed

beds to the use of alternative sludge-dewatering technologies, and (3) evaluate the potential for using reed beds for dewatering wastewater treatment plant sludges generated at U.S. Army installations.

Approach

A literature study was done to collect relevant background information on the use of reed bed technology to dewater sludge. A field inspection was done of representative reed bed units to evaluate existing reed bed operations. This information was analyzed to determine the applicability of reed bed technology to U.S. Army installations. Areas for further study were identified.

Scope

This report analyzed existing reed bed operations only. Investigation of the technical aspects of reed bed design and scientific principles behind reed bed operation were beyond the scope of this study.

Mode of Technology Transfer

It is anticipated that the information gained from this effort will be incorporated into an Public Works Technical Bulletin (PWTB), to be prepared and distributed by the U.S. Army Center for Public Works (USACPW), Fort Belvoir, VA.

2 OVERVIEW OF REED BED PROCESS

Overview

The reed bed process is an innovative process for sludge dewatering that combines the operating advantages of underdrained sand-drying beds with an added dewatering advantage derived from the active growth and activities of the common reed, genus *Phragmites*. A variety of stabilized sludges have been dewatered by this method, including aerobic and anaerobic sludges.

Reed beds are often constructed outdoors but may be sheltered (e.g., covered with roofs), or given an even greater degree of environmental control in greenhouses. Often reed beds are retrofitted to existing conventional sand-drying beds. In practice, reed beds are constructed similarly to sand-drying beds. Construction begins by excavating a number of parallel, rectangular trenches of planned dimensions, which include vertical sides, underdrains, and a sludge distribution system (Figure 1).

The excavated trench is lined with an impermeable liner to prevent exfiltration, and is filled with two sizes of gravel and a top layer of filter sand. The liner can be of any impermeable, durable material. (Several installations have employed precast Hypalon liners without any problems.) The side walls of the bed commonly consist of concrete wall of a sand-drying bed and approximately 120 cm (4 ft) of freeboard above the concrete wall to allow for sludge accumulation. The USEPA notes that freeboard above the sand layer should be at least 1 m (39 in.) to provide for long term sludge storage (USEPA September 1987).

While reed bed design may vary from installation to installation, depending on the local conditions, about 25 cm (10 in.) of gravel is added to cover the underdrain piping (USEPA September 1987) and the gravel is overlaid with about 10 cm (4 in.) of filter sand. Figure 1 shows optional details relating to influent, distribution systems and effluent collection.

Once the beds have been constructed, *Phragmites* reeds are planted, usually in the form of 1-ft plants or root stocks. *Phragmites* is well suited to this role as it is extremely tolerant of variable environmental conditions and has a high evapotranspiration rate. The reeds are planted atop the gravel layer, at a planting density of one plant per square foot. The bed is then flooded with water for a period of time varying from several days to several weeks, depending on the growth rate, to facilitate reed development.

Once the reeds are established, stabilized sludge is applied to the bed at regular intervals. While the sludge dries by evaporation, the growing reeds derive nourishment and moisture from the sludge, both stabilizing the sludge and reducing its volume (USEPA September 1987).

Unlike ordinary sand-drying beds, reed beds do not require regular removal of dried sludges. New sludge may be layered over the previous sludge applications. However, the reeds are normally harvested annually. The harvest is performed during the start of the plant's winter dormancy, typically using electric hedge clippers. The harvest is often taken after the first freeze, when the sludge is hard enough to walk on. Plants are cut to approximately 20 cm (8 in.) in size. The typical harvest yields about 25 tons/acre (Reed et al. 1988). It has been estimated that the sludge accumulation need only be removed from the reed beds after about 10 years of continued applications (Banks and Davis 1983a).

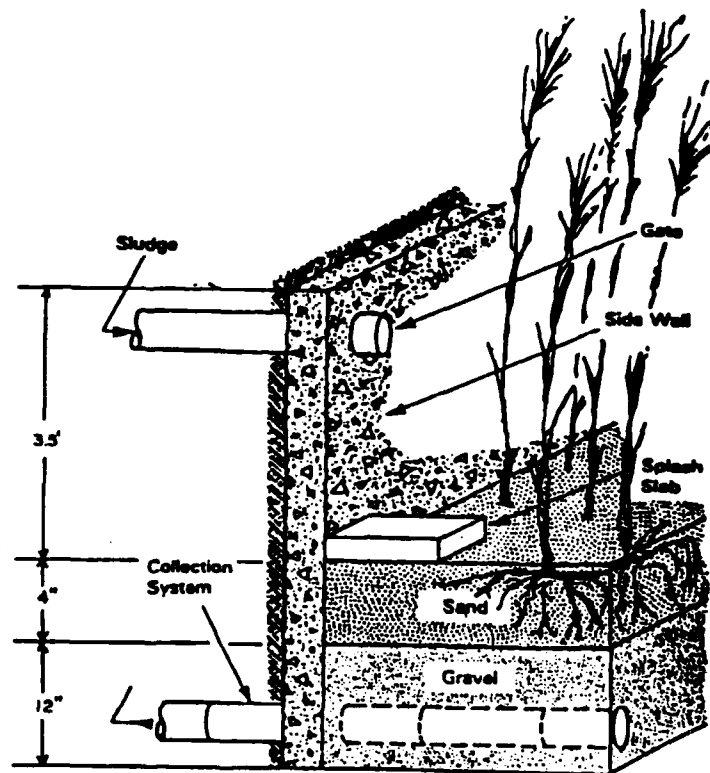


Figure 1. Cross-Section of Reed Bed System.

Literature Review

The term "constructed wetlands" generally refers to the use of artificial wetlands in treating wastewater, and has recently been applied to sludge dewatering. Such processes, which use relatively more land, but less energy and labor are becoming attractive alternatives for small communities (USEPA September 1988).

The interest in the aquatic wastewater treatment systems can be attributed to three factors:

1. Recognition of the natural treatment capabilities of plants, particularly as nutrient sinks and buffering zones
2. In the case of wetlands, emergence or renewal of aesthetic wildlife and other incidental environmental benefits
3. Rapid increase in cost of construction and operation associated with conventional treatment systems (USEPA September 1988).

The Reed Bed Treatment System (RBTS) is an alternative means of treating sewage by using emergent hydrophytes. Initially the use of emerging plants in treating wastewater was patented by Kaethe Seidel of the Max-Planck Institute, who studied the use of emergent plants in treating polluted water as early as the 1900s (Godfrey et al. 1985). In this application, known as "the root zone method," reeds were found to be more effective at oxygen transfer than cattails because of the deeper vertical penetration of the reed rhizome system (USEPA September 1988). In 1968, Kickuth began work in Germany to treat sewage by horizontal flow through a natural reed bed planted with the common reed, *Phragmites australis*.

(Cooper et al. 1990, p 7). Moreover, German researchers found that reeds could create oxidized zones within the sludge deposits that facilitate a sequence of mineralization, nitrification, and denitrification (Cooper et al. 1990, p 275). Later studies corroborated these findings (Winter and Kickuth 1985).

In addition to dewatering wastewater, reeds have been found extremely useful in drying dredged spoils. As early as 1932 *Phragmites* were used as a drying agent in Holland during land reclamation of the Zuider Zee (Brown 1981). More recently, reeds have been used in an Army Corps of Engineers funded study of using vegetation to dry dredged material (Biological Water Purification Inc. 1976). This study revealed that reed-planted spoil basins would sufficiently dry to walk on. Another beneficial aspect was that the root and rhizome system of *Phragmites* enhanced the porosity of the dredge deposits, thereby increasing drainage, preventing ponding, and allowing aeration.

A study in Usterbach, Germany, described the successful use of reeds in sludge treatment and dewatering, and spurred development of a working reed bed system for sludge dewatering in the United States. In Usterbach, three beds were planted (one [100 m²] control bed) to treat sludges from an activated sludge process. In this application, the reed beds were fed with sludge for 10 years without removing them, at rates of 8 to 12 cm of sludge (1 percent dry solids) every 10 to 14 days during 8 or 9 months. The control bed clogged after a few months. After 8 years of feeding, 18 m of liquid sludge had been applied to one of the beds, leaving only 36 cm of residue, yielding a volume reduction of 98 percent. Such a large reduction indicates that the reduction was due not only to dewatering, but also to mineralization (Cooper et al. 1990, p 261).

Banks and Davis summarized the interaction of sludge and reed beds to process "difficult to dry" sludges (1983a). They observed that "hydroxide slimes and sewage sludge" that dry quickly form a "closed, relatively small surface that strongly resists further drying by evaporation." They noted that the growth of plants with a multiple root system prevented the formation of this dense, "closed" surface and thus enhanced drying and evaporation. Plant growth absorbs water into the root system, and subsequently releases it to the atmosphere by transpiration. Plants most suitable for this action are those with a great need for water and a tolerance of changing environmental conditions.

Such plants transport oxygen to their root systems, promoting the intense biological activity described in the 1980 Usterbach study. This activity establishes a rich ecosystem, which includes earthworms and a resident microflora. Banks and Davis further speculated that the plants produced "root exudations" that were active against pathogens, and that the plants specifically showed an affinity for cadmium, zinc, manganese, and copper, a claim perhaps related to other claims of changes in various aromatic compounds (1983a). These researchers reported that 40 percent of the effluent volume passes through the bed within 6 hr, and that 70 to 80 percent of the flow passes through within 2 or 3 days. During the reed's vegetative period, evapotranspiration amounts to 40 percent of the influent volume.

The 1987 USEPA Design Manual for Dewatering Municipal Wastewater Sludges describes the reed bed process as an innovative technology. The manual provides information on installation of reed beds, which includes a description of liners, underdrains, gravel and sand particle sizes, and sludge loading. Average solids loading rates specified were 17 lb/sq ft/yr for 3 to 4 percent sludge concentrations, with annual sludge accumulations of 10 cm (4 in.). At this rate of accumulation, sludge is removed at the end of a 10-year cycle, along with the sand layer. The beds are taken out of operation 6 months prior to evacuation to allow time for the sludge to mineralize and for pathogens to be destroyed. This downtime makes multiple beds necessary. The USEPA also reports that the major advantage of the reed bed system is that it requires little maintenance in the way of sludge removal and bed cleaning. The major disadvantage is the need for annual reed harvesting. The USEPA also notes that the resulting annual reed harvest volume, along with 10-year remaining sludge volume, is still less than the volume requiring disposal during 10 years of a conventional sand-drying bed operation.

3 FINDINGS

Background Data

Questionnaire

To define, gather, and focus relevant information and data needs, a list of reed bed sludge treatment installations was compiled and a questionnaire was developed. The questionnaire was mailed to 32 known reed bed operations in 1990, including recently discontinued facilities. An additional 12 new plants with reed bed operations were contacted in 1992. The Appendix to this report contains a copy of the sample questionnaire.

The questionnaire was divided into seven areas of inquiry:

1. Design data
2. Construction costs
3. Operation and maintenance
4. Reed bed performance
5. Startup data
6. Replanting data
7. General information relating to reed bed performance.

The goal of the questionnaire was to form the basis for data collection to take place during later field visits, and thereby to obtain as much information as possible for evaluation. To extract good responses, the respondents were encouraged to answer only the questions that could be readily answered, and the authors helped elicit answers to more difficult questions at the time of the site visit. Researchers followed up by telephone to clarify or supplement the information gathered by questionnaire interview.

In all, 14 of the initial (1990) questionnaires and 10 of those sent in 1992 were returned to the authors completed to various degrees. The questionnaire formed the basis for the site visit queries that were made during interviews with the wastewater treatment plant personnel. As they were received, the questionnaires were reviewed, results were summarized, and as required, followed up by telephone calls.

Site Visits

Six site visits and interviews were conducted at reed bed facilities in New Jersey. The plant operators and/or managers were interviewed in an attempt to obtain available information regarding the reed bed design criteria, construction costs, operation and maintenance requirements, costs and bed performance and closing and replanting data. Table 1 lists the reed bed facilities evaluated for this study. Data was taken on a total of 24 facilities; 6 were visited.

Engineering Evaluation

Based on the gathered data, reed bed performance was evaluated by comparing it to conventional methods, i.e., sand-drying beds. The evaluation was formatted to be similar to the questionnaire; the categories used to compare the reed bed system with conventional sludge dewatering were:

1. Design criteria (including solids loading rate)
2. Cost of construction/implementation
3. Operation and maintenance

Table 1
Reed Bed Plants Studied

Installation	Location
Reed bed plants studied, but not visited:	
Adamstown Wastewater Treatment plant	Adamstown, PA
Bally Borough	Bally, PA
Berks Montgomery Municipal Authority	Gilbertsville, PA
Bethel Wastewater Treatment Plant	PlantBethel, ME
Borough of Highstown Wastewater Treatment Plant	Highstown, NJ
Borough of Royersford	Royersford, PA
Ellsworth Pollution Control Facility	Ellsworth, ME
Fleetwood Sewage Treatment Plant	Fleetwood, PA
Gordon Wastewater Treatment Plant	Potsville, PA
Leesport Borough Authority	Leesport, PA
Myerstown Elco Wastewater Treatment Plant	Myerstown, PA
Northern Lancaster Co. Authority	Denver, PA
Old Bridge Township Board of Education	Old Bridge, NJ
Saxton's River Wastewater Pollution Control Facility	Saxton's River, VT
Schwenksville Borough Authority Plant	Schwenksville, PA
Topton Sewage Treatment	Topton, PA
Wabash WWTP	Wabash, IN
Wallingford Fire District #1Wastewater Treatment Plant	Wallingford, VT
Reed bed plants studied and visited	
Beverly Sewerage Authority	Beverly, NJ
E.R. Johnstone Training and Research Center	Bordentown, N
Malboro Development Center	Malboro, NJ
Military Ocean Terminal	Bayonne, NJ
Riverton Sewage Treatment Plant	Riverton, NJ
Schooley's Mountain Sewage Treatment Plant	Long Valley, NJ

4. Type of sludge
5. Winter conditions
6. Sludge residue volume.

These comparisons were compiled and are tabulated in Chapter 4. Tables 2 and 3 list the engineering and operational design parameters for each investigated reed bed facility:

1. Solids loading rate
2. Sludge loading rate
3. Annual sludge loading rate
4. Loading rate
5. Sludge depth
6. Solids content
7. Bed size/number of beds
8. Source of sludge
9. Cost of construction/implementation
10. Operation and maintenance
11. Infestation problems/treatment
12. Winter application
13. Density and depth
14. Initial application.

Table 2
Engineering Design Parameters

Plant	Solids		Hydraulic		Annual Sludge Loading Rate	Depth of Sludge	Solids Content	Individual Bed Size	No. of Beds	Total Area	Sludge Source	Cost of Construction/Implementation
	(lb/sq ft/yr)	(kg/m ² /yr)	Loading Rate (gal/sq ft/yr)	(m ³ /m ² /yr)	(gal/yr)	(in.)	(%)	(sq ft)		(sq ft)		
A	10.43		83.3			N/A	1.5	3,000	1	3,000	Iron filtrate*	N/A
B	51		3.4		18,480	6 in./year; 24 in. total/ 4 years accumulation	0.5-3 (H) 3.5 (L) 0.5	900	2	1,800	Secondary, anaerobically digested	N/A Sand-drying bed beds retrofitted for reeds
C	N/A		N/A		N/A	N/A	2	800	2	1,600	Secondary, aerobic	Approximately \$7,000 converted sand-drying beds
D	14.9 72.9		89.3 3.63		600,000	6-8 in./year	1-2 (H) 2.5-3.0 (L) 0.5-1.0	840	8	6,720	Secondary, aerobic	N/A
E	9.3 45.5		5 - 55.5 0.2 - 2.26		23,000-250,000 gal/yr	0.5 in./year	2	2,250	2	4,500	Secondary, digested aerobic	In-house conversion from sand beds to reed beds, built up walls for additional freeboard
F	14.9 73		179 7.3		416,000	N/A	1 (H) 3 Winter (L) 0.6	581	6 Total 4 Operating	3,486 2,324	Secondary, aerobic	N/A
G	6.0 29.4		17.85 0.7		144,000	9-11 in./year accumulation	4	1,344	6	8,064	Digested, aerobic	Prefabricated beds w/Hypalon liner and underdrains
H	15.2 74.4		18.2 0.74		200,000	1-2 in.; 12 in. accumulated in first bed/year	8-10	2,750	4	11,000	First bed primary Imhoff, all other beds purflux chemically oxidized	\$15,000 planting, startup
I*	N/A		N/A visually evaluated		N/A	N/A	N/A	576	4	3,456	Primary Imhoff sludge	N/A
J	21.3 104.2		127.5 5.2		520,000	4 in. each application; 20 in. over the past 3 years	1-2	680	6	4,080	Secondary, aerobic	\$25,000 Construction of 4 beds; retrofitted 2

*Reed beds were used for iron filtrates at this facility per direction from state regulatory agency. Sand-drying beds were used to treat sewer sludge.

Table 2 (Cont'd)

Plant	Solids Loading Rate (lb/sq ft/yr) (kg/m ² /yr)	Hydraulic Loading Rate (gal/sq ft/yr) (m ³ /m ² /yr)	Annual Sludge Loading Rate (gal/yr)	Depth of Sludge (in.)	Solids Content (%)	Individual Bed Size (sq ft)	No. of Beds	Total Area (sq ft)	Sludge Source	Cost of Construction/Implementation
K	21.7 106	52 2.12	125,000	0.5 in. each application	5 (Avg.) (H) 7 (L) 3	400	8 Total 6 Operating	3,200 2,400	Secondary, aerobic package plant	N/A In-house maintenance provided construction; retrofitted 6 beds w/freeboards
L	17.2 84.2	83 3.38	182,000	2.5 in. each application 12-18 in. accumulation	2-2.5 (H) 2.5 (L) 2.0	1,100	2	2,200	Digested, aerobic	\$7,700 For Planting
M	5.0 24.5	20 0.81	180,000	1-2 in. initial sludge application	2-3	900	10	9,000	Anaerobically digested	\$83,000 Includes 2x8 pressure-treated side walls with Hypalon liners, underdrains
N	3.3 16	39.6 1.61	380,000	4 in. each application	1% (L) <0.5%	2,400	4	9,600	Anaerobically digested	Local contractors retrofitted sand beds; high walls installed for freeboard.
O (0.3 MGD)	9.2 45	47 1.91	88,000	4 in.	(H) 4.4 (L) 0.3	1,880	1	1,880	Secondary aerobically stabilized oxidation ditch	Approximately \$4,500 for retrofitting from sand-drying beds
P (0.175 MGD)	4 19.5	30 1.22	96,000	8-10 in./ application 18 in. accumulation/yr	(H) 2.0 (L) 1.2	800	4	3,200	Aerobically digested charcoal filter	Retrofitted from sand-drying beds
Q (1.9 MGD)	12 57	7 0.3	14,000	2 in./ application	(H) 8.0 (L) 6.0	1,980	1	1,980	Secondary anaerobically digested	Retrofitted from sand-drying beds
R (0.54 MGD)	5.6 27.5	13.4 0.55	47,000	1 in./ application	(H) 6.0 (L) 4.0	A 1,500 B 2,000	2	3,500	Primary secondary anaerobically digested	Retrofitted from sludge drying beds \$30,000 for retrofit
S (0.4 MGD)	7.3 35.5	50 2.03	1,080,000	2-4 in. accumulation/yr 2 in./ application 2.5 in. accumulation/yr	(H) 2.5 (L) 1.0	5,400	4	21,600	Secondary aerobically	Newly constructed beds
T (0.2 MGD)	2.3 11	26.3 1.07	126,000		(H) 2.0 (L) 1.0	2,400	2	4,800	Secondary aerobically Stabilized	Retrofitted from sand drying beds \$15,000 for retrofit

Table 2 (Cont'd)

Plant	Solids		Hydraulic		Annual Sludge Loading Rate (gal/yr)	Depth of Sludge (in.)	Solids Content (%)	Individual Bed Size (sq ft)	No. of Beds	Total Area (sq ft)	Sludge Source	Cost of Construction/Implementation
	Loading Rate (lb/sq ft/yr)	(kg/m ² /yr)	Loading Rate (gal/sq ft/yr)	(m ³ /m ² /yr)								
U (0.7 MGD)	2		24				(H) 5.5 (L) 4.5	5,000	6	30,000	Primary, secondary anaerobically digested	Newly constructed beds \$750,000 for new beds
	9		0.98		720,000	5 in. accumulation/yr						
V (0.15 MGD)	8		48			6-8 in. accumulation/yr	(H) 2.5 (L) 2.0	1,250	10	12,500	Secondary, aerobically stabilized	Newly constructed beds \$200,000 for new beds
	39		1.95		600,000							
W (0.125 MGD)	6.2		50			4 in. application	(H) 2.0 (L) 1.0	400	6	2,400	Primary, secondary aerobically stabilized	Retrofitted from sand-drying beds \$1,000 for retrofit
	30.5		2.03		120,000	8 in. accumulation/yr						
X (2.75 MGD)	2.3		4			1.8 in. application	(H) 7.0 (L) 5.0	6,004	7	42,028	Primary, secondary anaerobically digested	New beds \$392,121 for new beds
	11		0.16		154,000							

Table 3

Operational Design Parameters—Reed Bed Study

Facility and Location	Operation and Maintenance				Infestation Problems/Treatment	Winter Application	Density & Depth	Initial Application
	Reed Bed	Harvesting						
Plant A	Harvested reeds averaged a volume of 219 cu ft per year	3 days; reeds cut with hedge trimmer			Morning glory vines choked the reeds	Not available (N/A)	N/A	N/A
Plant B	Harvested reeds hauled to landfill	8 hr; electric hedge clippers; harvest when sludge bed is frozen.			Aphid control by lady bugs	No limitation on sludge application	N/A	N/A
Plant C	Two employees at 3 hrs/day, \$7.50/hr	Harvested by sickle, late fall after 1st freeze then burned.			N/A	No limitation on sludge application	N/A	Plantings 12-in. high inundated with decant and well water

Table 3 (Cont'd)

Facility and Location	Operation and Maintenance				Infestation Problems/Treatment	Winter Application	Density & Depth	Initial Application
	Reed Bed	Harvesting						
Plant D	Four employees; two administrative three pickups one pump station	8 hr; green mulch cut w/weed wackers with saw blades in Dec.-Jan. then composted.			Aphid control by lady bugs	No sludge applied during Dec-Mar.	6-8 in. deep plants	Inundated with treated effluent water, 2-3 ft high, 1-2 mos. elapsed before sludge applied
Plant E	(1) Full-time employee	Not harvested yet			Aphid control by spraying (insecticide)	8000 gal/20 days	2 ft between plants 6-in. deep	Immediately after planting
Plant F	One administrative two assistants weeding needs one person; done every 2 months 144 hrs. annually	24 hr; done [3 days] some time in Oct-Dec			Aphids controlled by lady bugs and an exterminator comes once in every 2 months.	Cease application during subfreezing temperatures	18 in. apart 3-4 in. deep	3 weeks heavy watering before sludge application
Plant G	2-3 employees; saved over \$56,000 in hauling costs	Done with a hedge trimmer; takes about 2 days.			Aphids controlled by lady bugs	No application during February	Every foot	Inundated with secondary water for 2 days; 1 week later applied sludge.
Plant H	One administrative two employees	18-in. electric sickle bar			Aphids controlled by lady bugs	Sludge application not limited during winter	One plant per sq ft	Approximately 3 weeks after planting
Plant I	Two employees takes 2 days for weeding operation (24-hrs)	Cut reeds are landfilled			Aphids controlled by lady bugs	N/A	N/A	Approximately 6 months after planting
Plant J	30 minutes to apply sludge	N/A			Aphids/lady bugs lace wings	Jan-March no sludge applied due to frozen weather	250-300 plants	18 days after planting (small amount applied)
Plant K	One part-time employee	Annually reeds are hand cut during fall			Aphids/lady bugs	Sludge application not limited during winter	1 plant per sq ft of bed	As soon as plants start growing, "a few weeks"

Table 3 (Cont'd)

Facility and Location	Operation and Maintenance				Infestation Problems/Treatment	Winter Application	Density & Depth	Initial Application
	Reed Bed	Harvesting						
Plant L	Two employees approx 1 hr/wk	Not yet done			Aphids/concentrate sprayed	N/A	One plant per sq ft and 4-in. deep in sand	1.5 months after planting
Plant M	One administrative one operational part-time, sludge tank trucks, irrigation pumps @ \$1,500 annually	During winter; season using; weed wackers			Aphids/malithion sprayed	Limited during cold weather but the duration of time is not available	One plant per 1.5 ft radial spacing and 6-in. depth	"Several weeks" after planting
Plant N	Two employees	Not yet done			Aphids/initially, lady bugs then sprayed	No application 21-28 days during winter season	6-in. depth of planting	Approximately 3 days after planting
Plant O	5 manhours for reed operations per year \$50 annual O&M	Annually in January; with a weed eater; with a blade Volume: 3 cu ft			No infestation	21-24 days between application	6 in. at initial application	4 in. applied initially; 2 in. after 2 days
Plant P	Two or three employees 120 manhours/yr \$2,000 annual O & M	Annually in December; with hand held gasoline; weed wacker			Spray insecticide for aphid control	N/A	N/A	Few weeks after planting
Plant Q	One or two employees 20 manhours/yr	Annually in January; with a gas-powered brush cutter and rake			Aphid control for first year	N/A	N/A	2 months after planting
Plant R	Four or five employees 425 manhours/yr \$3000 annual O&M	Annually in January; with a weed wacker; with a thich brush blade			Aphid control for first year with lady bugs	21 days between application	84 in. at initial application	4 weeks after planting
Plant S	40 manhours/yr \$500 annual O&M	Expect to harvest annually			N/A	No restriction to application	6 in. at initial application	6 weeks after planting
Plant T	30 manhours/yr \$50 annual O&M	Annually in winter; with hand and hedge; trimmer and rake			Aphid control during hot months	21 days between applications	N/A	N/A

Table 3 (Cont'd)

Facility and Location	Operation and Maintenance				Infestation Problems/Treatment	Winter Application	Density & Depth	Initial Application
	Reed Bed	Harvesting						
Plant U	200 manhours/yr \$4,000 annual O&M	Annually in January with sickle bar mower and hand rakes			Aphid control by spraying	42 days	9 in. at initial application	1 mo. after planting
Plant V	200 manhours/yr \$6000 annual O&M	Annually in winter with brush cutter			Aphid control by spraying	21 days between applications	12 in. at initial application	7 days after planting
Plant W	65 manhours/yr \$1000 annual O&M	Annually in winter with weed trimmer			Aphid control during first year	21-24 days between applications	6-12 in. at initial application	2 weeks after planting
Plant X	100 manhours/yr	Not yet harvested			N/A	21 days between applications	N/A	Immediately after planting

Plant Data

Most of the earliest research on reed beds was done in Germany. However, there were no reed bed operations in the United States until the late 1980s. The most commonly used reed in the United States is *Phragmites*, which is an extremely tolerant plant as noted in the literature and by the USEPA.

The surveyed reed dewatering beds were fed with either aerobic stabilized sludge or anaerobic digested sludge. Of the facilities surveyed, 14 fed aerobic stabilized sludge to the reed beds; 7 fed anaerobic digested sludge; and 2 fed primary Imhoff sludge.

Most of the reed beds were located in the northeastern United States (New Jersey, Pennsylvania, Maine, and Vermont). The oldest wastewater treatment facility in the United States is in New Jersey, with an operating history of 8 years. Most of the other facilities were relatively new. Table 4 lists the 47 currently operating treatment facilities. The increasing number of facilities suggests that reed bed dewatering is becoming recognized as an effective and efficient sludge-dewatering method.

Plant Capacity

Of the facilities dewatering aerobic stabilized sludge, the maximum plant capacity (plant S) was 0.4 MGD (million gal/day) with a total reed bed area of 21,600 sq ft, and an annual sludge loading rate of 1,080,000 gal/yr. The minimum plant capacity (plant W) was 0.125 MGD with a total reed bed area of 2400 sq ft and an annual loading sludge rate of 120,000 gal/yr.

Of the facilities dewatering anaerobic digested sludge, the maximum plant capacity (plant X) was 2.75 MGD with a total reed bed area of 42,028 sq ft and an annual sludge loading rate of 154,000 gal/yr. The minimum plant capacity (plant R) was 0.54 MGD with a total reed bed area of 3500 sq ft and an annual sludge loading rate of 47,000 gal/yr.

Bed Sizes

Most of the surveyed reed bed facilities were retrofitted from existing sand beds. The major modification was the addition of freeboard to accommodate increasing sludge layers.

The largest reed bed facility (plant S) dewatering aerobic stabilized sludge has a total bed area of 21,600 sq ft (4 beds each of 5400 sq ft) and the smallest facility (plant C) has a reed bed area of 1600 sq ft (2 beds each of 800 sq ft.)

The largest reed bed facility (plant X) dewatering anaerobic digested sludge has a total reed bed area of 42,028 sq ft (7 beds each of 6004 sq ft) and the smallest facility (plant B) has a reed bed area of 1800 sq ft (2 beds each of 900 sq ft).

Hydraulic Loading Rate

Figure 2 shows the correlation between the percent solids content and actual hydraulic loading for aerobically stabilized and anaerobically digested sludge. Table 5 gives hydraulic loading data.

Table 4

Known Reed Bed Operating Systems (1 June 1991)

Location	Started Operation	Operator and Contact
Amity Township WWTP, PA	04/91	Leroy Newswanger 215-385-3400
Ancora State Hospital Ancora, NJ	11/85	Ronald Vorndran 609-561-1700
Bally Borough WWTP, PA	10/90	Robert Moll 215-845-2351
Bay Side Prison, NJ	11/85	John Liebrand 609-785-0040
Berks-Montgomery Municipal Authority, PA	06/91	James Brady 215-367-1460
Bethel, ME	09/88	Rob Gunderson 207-824-2105
Beverly, NJ	04/85	Fred Weller 609-387-0372
Birdsboro, PA	11/88	Pat Mamarella 215-582-2860
Borough of Adamstown WWTP, PA	04/90	John Bennetch 215-484-4234
Borough of Orwigsburg, PA	07/89	Joe Collins 717-366-3100
Borough of Royersford, PA	08/90	Michael J. Claflin 215-948-3223
Borough of Slatington, PA	10/91	Craig Labold 215-767-5871
Borough of Tipton, PA	07/89	Russ Pilgrit 215-682-7875
Caribou, ME	07/88	Emery Knowlton 207-493-3125
Castleton, VT	07/88	Dick Steele 802-468-5315
Delaware Valley Industrial Sewage Co.	05/89	Herman Walker 215-643-2190
Fort Washington, PA Ellsworth, ME	08/88	Jim Dennison 207-667-7315
E.R. Johnstone Training Center	07/85	Bruno Gentile 609-298-2500 ext. 2005
Bordentown, NJ Essex County Hospital	05/86	Greg White 201-228-8000
Cedar Grove, NJ Fleetwood, PA	04/89	Buddy Rauenzahn 215-944-9361
Gordon WWTP, PA	09/91	Kent W. Brugler 717-622-8240

Table 4 (Cont'd)

Location	Started Operation	Operator and Contact
Greencastle, IN	11/89	Charlene Nicholas 317-653-3394
Leesport Borough Authority WWTP, PA	05/90	Timothy J. Lecker 215-926-2060
Maidencreek, PA	11/89	Eric Burkett 215-926-4140
Malboro Development Center Malboro, NJ	04/86	Bill Sandow 201-946-8100 ext. 2634
Military Ocean Terminal Bayonne, NJ	04/84	Hans Berger 201-823-7727
Myerstown-Elco WWTP, PA	10/90	Larry M. Fair 717-866-5826
Northern Lancaster Co. Authority, PA	09/90	Tim Myers 215-445-7553
Old Bridge, NJ Board of Education	06/85	Julius Logan 201-360-4507
Randolph, VT	06/88	Paul Stratton 802-728-9079
Robeson, PA	04/90	Dean Miller 717-626-2172
Saxton's River, VT	05/86	Budd Carle 802-869-2725
Schwenksville Borough Authority WWTP, PA	05/91	Barry Ludwig 215-287-7772
Seal Harbour, ME	05/87	Jim Pelletier 207-276-5544
Shoemakersville, PA	05/89	Dave Smith 215-562-2128
Sinking Spring, PA	05/89	Dave Miller 215-678-7223
Southold, NY	12/86	Ray Jacobs 516-734-5211
Sunapee, NH	05/88	Jim Leland 603-763-2121
Terre Hill Borough, PA	05/89	Bob Rissler 215-445-6248
U.S. Army, Fort Campbell	11/89	James Evans 502-798-3122
U.S. Navy Group Security Winter Harbour, ME	06/88	Tom Severance 207-963-5534
Wabash WWTP, IN	09/91	Vincent J. Bauco 219-563-2941

Table 4 (Cont'd)

Location	Started Operation	Operator and Contact
Wallingford, VT	06/86	Clovis Leach 802-446-2325
Warner, NH	08/87	Vicky Abbey 603-456-3890
Washingtown Township MUA Schooley's	08/85	Bob Gannon 201-876-4500
Mountain, NJ		Gerry King
Winter Harbour, ME	05/87	207-963-5579
Woodbine Developmental Center, NJ	06/90	609/861-2164

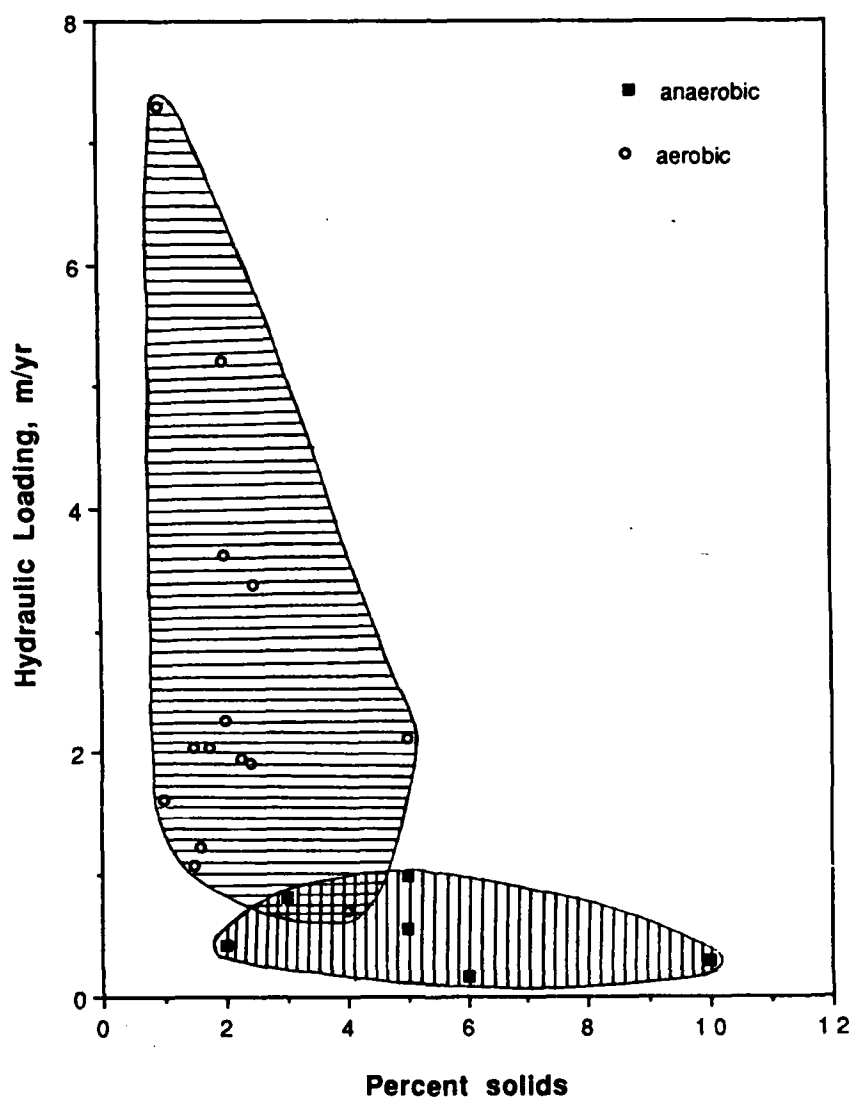


Figure 2. Hydraulic Loading Rate vs. Percent Solids.

Table 5
Loading Data

Plant	%Solids	Hydraulic Loading Rate m/yr	Solids Loading Rate lb/sq ft/yr
Anaerobic digested sludge			
B	2	0.42	2.6
M	3	0.81	5.0
Q	10	0.30	5.7
R	5	0.55	5.6
U	5	0.98	9.7
X	6	0.16	12.3
Aerobic stabilized sludge			
		3.63	14.9
D	2	2.26	9.3
E	2	7.30	14.9
F	1	0.70	6.0
G	4	5.20	21.3
J	2	2.12	21.7
K	5	3.38	17.2
L	2.5	1.61	3.3
N	1	1.91	9.2
O	2.4	1.22	4.0
P	1.6	2.03	7.3
S	1.75	1.07	3.3
T	1.5	1.95	8.0
V	2.25	2.03	6.2
W	1.5		

Of the facilities dewatering aerobic sludges, the maximum loading (plant F) was $7.3 \text{ m}^3/\text{m}^2/\text{yr}$ (7.3 m/yr) (179 gal/sq ft/yr) and the minimum loading rate (plant G) was $0.73 \text{ m}^3/\text{m}^2/\text{yr}$ (0.73 m/yr) ($17.9 \text{ gal/sq ft/yr}$). The maximum loading rate for the facilities dewatering anaerobic digested sludges (plant U) was $0.98 \text{ m}^3/\text{m}^2/\text{yr}$ (0.98 m/yr) (24 gal/sq ft/yr) and the minimum (plant X) was $0.16 \text{ m}^3/\text{m}^2/\text{yr}$ (0.16 m/yr) (4 gal/sq ft/yr).

Figure 2 shows yearly average operational hydraulic loading range on the reed beds. Hydraulic loading appears to be insensitive to solids content in the sludge. The hydraulic loading rates for anaerobic sludge are much lower compared to that of aerobic sludge. One hypothesis is that the evapo-transpiration of reeds can be higher for aerobic sludge than anaerobic sludge.

It is critical to develop logical hydraulic loading criteria to implement this technology at Army wastewater treatment plants.

Solids Loading Rate

Figure 3 depicts a correlation between the percent solids content and the actual annual solids loading for aerobically stabilized and anaerobically digested sludge. Table 5 provides solid loading data. Although aerobic sludge has lower percent solids, its solid loadings are much higher than anaerobic sludge. It was also noted that about 70 percent of data points are within the dotted boundary between 12.3 and 2.6 lb/sq ft/yr.

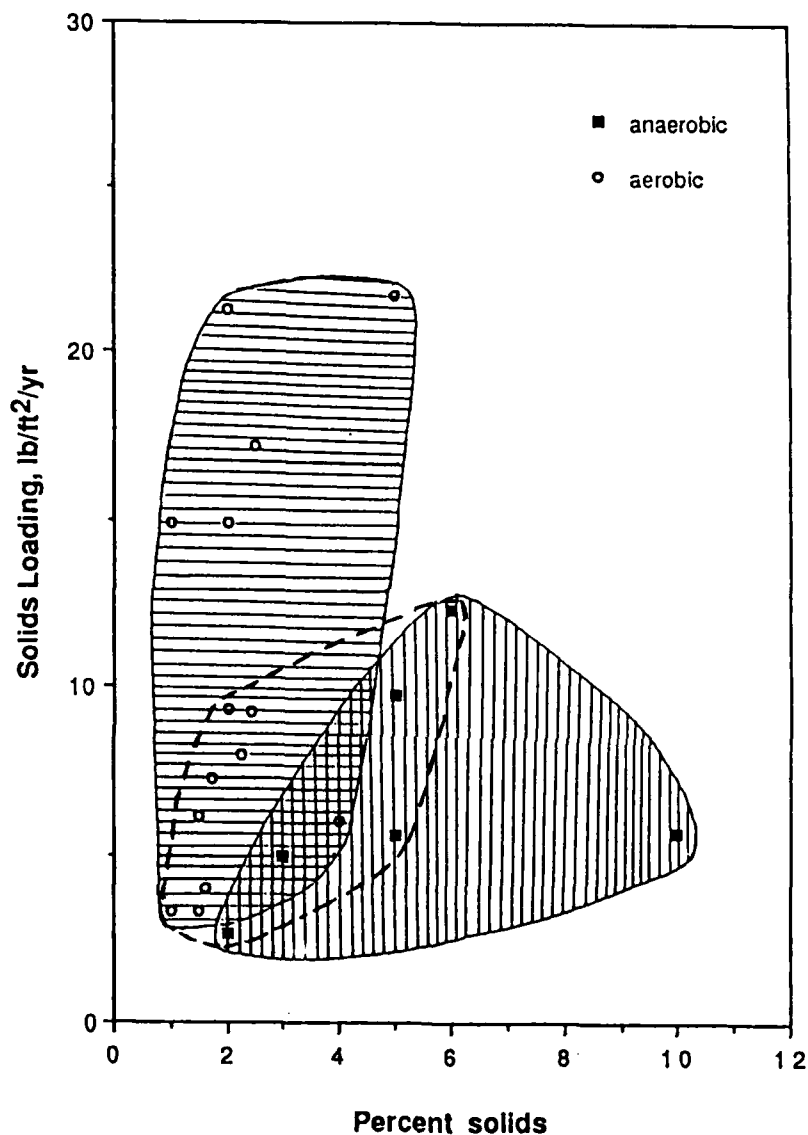


Figure 3. Solids Loading vs Percent Solids.

Of the beds dewatering aerobic stabilized sludge, the maximum solids loading rate (plant K) was $106 \text{ kg/m}^2/\text{yr}$ (21.7 lb/sq ft/yr) and the minimum (plants N,T) was $16 \text{ kg/m}^2/\text{yr}$ (3.3 lb/sq ft/yr). Of the beds dewatering anaerobic digested sludge, the maximum solids loading rate (plant X) was $60 \text{ kg/m}^2/\text{yr}$ (12.3 lb/sq ft/yr) and the minimum (plant B) was $13 \text{ kg/m}^2/\text{yr}$ (2.6 lb/sq ft/yr).

Figure 3 shows the solids loading rate vs. the percent solids. The solids content of aerobic sludge has a small range (1 to 5 percent) whereas that of anaerobic sludge has a wide range (2 to 10 percent (Table 5). Figure 3 shows that, for aerobic sludge, the solids content of the sludge is low whereas the

solids loading rate is very high. On the other hand, for anaerobic sludge, the solids content of sludge is quite high whereas the solids loading rate is not as high as the aerobic sludge.

Figure 3 depicts yearly average operational solids loading rate on the reed beds at each specific plant, given the type of sludge and solids content of the influent sludge to be dewatered.

By comparison, in 1987, the USEPA reported that the average solids loading rate for 16 operating facilities in New Jersey, New York, and North Carolina was about $81 \text{ kg/m}^2/\text{yr}$ (17 lb/sq ft/yr), a figure USEPA noted to be on the lower end of the loading rates for conventional sand-drying beds (USEPA, September 1987).

The factors that may affect solids loading rate include the weather conditions (summer/winter), type of sludge, percent solids, number of beds in operation, area of beds, and hydraulic loading.

It is critical to develop logical solids loading criteria to implement this technology at Army wastewater treatment plants.

Construction Costs

Some of the surveyed facilities were able to provide the costs for retrofitting reed beds into existing sand beds. Most of the facilities were retrofitted from existing sand-drying beds. Retrofitting costs are especially relevant to the Army because its installations already operate sand-drying beds, which can be retrofitted easily.

Of the facilities that provided costs of retrofit, the highest cost incurred was \$83,000 (plant M) for 10 beds (total area 9,000 sq ft), which is $\$100/\text{m}^2$ ($\$9.30/\text{sq ft}$). The least cost incurred was \$1,000 (plant W) for 6 beds (total area 2,400 sq ft), which is $\$5.0/\text{m}^2$ ($\$0.45/\text{sq ft}$).

However, some of the newly constructed reed beds were expensive to build. The highest cost reported for the new construction was \$750,000 (plant U) for 6 beds (total area 30,000 sq ft), which was $\$269/\text{m}^2$ ($\$25/\text{sq ft}$).

None of the facilities could provide cost data for the construction for the initial sand-drying beds. The economic factor in the retrofit was the primary cost for reed acquisition, planting, addition of freeboard to allow for sludge accumulation, and other retrofitting such as plumbing, filter media, liners, and underdrains.

Start-up

After construction, the beds are evenly graded and the reed stock is planted. *Phragmites* is usually obtained from a commercial grower of a nearby wetland, and the reeds are usually planted during the growing season. Normally the root stock (1-ft plant) is planted in the beds using a 30-cm (1-ft) center spacing between plants. The USEPA also reported similar results when reed stocks were planted at 30-cm (1-ft) centers on a gravel layer, to a depth of about 10 to 15 cm (4 to 6 in.).

After initial planting, the beds are flooded with water, maintained, and allowed to enter a vigorous, normal growth phase before sludge is applied. Usually the establishment of a healthy reed bed stand requires several weeks of growth. The study results have shown that the time elapsed between the initial planting and the initial sludge application varied considerably due to weather conditions. Some of the

plants (plants K, M, P, and R) reported that only a "few" or "several" weeks elapsed after planting, while others (plants E, N, and X) reported that they had applied sludge immediately after planting. Some facilities (plants D, Q, and U) waited 1 to 2 months before sludge application. The USEPA reports that the beds are usually flooded with water to a depth of about 10 cm (4 in.) for several weeks to encourage plant development, and that sludge is not applied until the plants are well established (September 1987).

Operation and Maintenance

Sludge Application and Monitoring

After the reeds have established, the treated sludge, usually ranging from 0.5 to 7 percent solids, is applied in multiple layers, on average ranging from 5 to 10 cm (2 to 4 in.) per bed. Sludge application ranged from weekly to bimonthly loadings. Most often, dosing to the beds is rotated among the beds.

Unlike the sand-drying beds, the previously applied and dewatered sludge is allowed to remain on the bed, and new layers of sludge are applied directly on top of the old ones. The root system of the *Phragmites* allows vertical pathways for the water to drain through. Therefore, subsequent sludge layers will be dewatered via these passageways. However, recent data indicate that the underdrainage is considerably less than what was expected. The facilities reported that the underdrainage would last for a day or two after the sludge application. Most of the facilities needed an employee to regulate the sludge applications. This employee would also visually assess the beds for possible problems such as weed or insect (aphid) infestations, and collect sludge samples, as required.

Some of the facilities were required to monitor the sludge applied to the beds through regular testing prior to application. New Jersey requires several forms to be filled with tested parameters, including percent solids, percent volatiles, pH, biological oxygen demand (BOD), EP Toxicity (now toxicity characteristics leaching procedure [TCLP]) and coliform counts. Some facilities have reported testing in New Jersey and that their results were within the specified standards. Some operators went beyond requirements, and reported testing their sludge even after application to the beds; however analysis of post-application test data and results was beyond the scope of this study.

Sludge application and visual monitoring varied in the length of time needed, although it is not a tedious process. At one of the facilities, this operation, including sludge sampling 5 days/week, required about 30 minutes to 1 hr/day.

Once sludge has been applied to the reed beds, minimal attention is required until the next sludge application. Unlike sand-drying beds, sludge removal is not required on a regular basis. The USEPA reports that this aspect of the reed beds makes it a powerful tool compared to conventional sand-drying beds (September 1987). Both the plant operators and the reed suppliers predict that the sludge can remain on the beds for approximately 10 years. USEPA (September 1987) also estimates a 10-year cycle for the reed beds in operation before the sludge is removed from the beds.

Harvesting

Once a year, usually during the late fall or winter, the reeds must be harvested from the beds. Some of the reed bed personnel prefer to carry out this operation when the beds are frozen. The survey results show that the time required for harvest ranges from 1 to 3 days, depending on the bed size, method used, and the number of beds to be harvested. Normally, two workers are required, one to cut and the other to collect and remove the reeds. The USEPA recommends the annual harvesting of reeds when the plants are dormant, but before they shed leaves (September 1987).

Harvesting does not require any specialized or heavy mechanical equipment. It is normally performed manually with hedge clippers, sickles, or a mechanical "weed whacker" (a gasoline powered portable saw with a 230-mm x 1.8-mm blade). Similar to the homeowner's weed whacker, it is operated with an extended handle to cut the reeds to a height of about 20 cm (0.7 ft). The harvested reeds may then be disposed of by hauling to local landfills, composting, or burning. Since harvesting is the major manpower requirement and disposal of harvested reeds is no simple problem, other alternatives including no-harvest and on-site disposal should be considered.

Weeding

The only major operation regarding the maintenance occurs during harvesting, when any weeds that have grown among the reeds are removed. Weeding may not be necessary at every facility, especially after the first growing season. While plants are being established, and before new growth occurs, it may be necessary to weed out tomato plants (*Lycopersicon Esculentum*). After the reeds have become established, *Phragmites* generally forms a dense stand that precludes the growth of other species.

The weeding operation requires from 1 to 3 days and is usually carried out by hand using 1 to 3 persons, depending on the density of weeds. Two facilities recorded the longest time—about 200 manhours per year—on overall maintenance. Another plant, at the extreme upper end of the weeding requirement, expends about 144 manhours per year, whereas a small plant estimates about 2 hr per bed, or a total of 1 or 2 days for the 8 beds at the facility. The extensive amount of weeding required at the facility (144 hr) is attributed to the annual reed die-off. The heat generated at this greenhouse-enclosed facility prohibits the formation of the usual dense *Phragmites* stands. Other weed species found at this facility are *Polygonum Spp.* and *Panicum Dichotomiflorum* (zig-zag grass). Another facility that had discontinued the reed bed system, reported problems with morning glory vines (family *Convolvulaceae*) choking the *Phragmites*.

Sludge Removal

According to the operators and the reed suppliers, the reed beds should be fully functional for a period of 10 years, although this figure could vary between 6 and 10 years. The USEPA estimates the cycle time as 10 years (September 1987). However, at the time of this survey, no facility has operated a reed bed for a full 10-year cycle.

Of the existing U.S. facilities, 6 are reported to have a maximum of 7 to 8 years of operating history with reeds. The earliest evacuation was expected to occur in 3 to 4 years. However, the reeds have been fully functional according to the operators' evaluation.

Sigmatron Biological, Inc. recommends that when the sludge accumulation reaches 90 cm (3 ft), the reed beds should be entirely evacuated (including the upper layer "filter" sand removal and replacement) and new reeds planted. To reduce pathogens, it is further recommended that the facility stop sludge application about 6 months before evacuating the existing beds. The USEPA also recommends that, if a bed is to be cleaned, sludge applications should be stopped in the early spring and the sludge residue and sand removed by winter (1987). Since no operational data is available associated with the USEPA's new sludge regulations (Part 503), more research is needed in the pathogen reduction on reed beds.

Winter Operations

The reeds' dormancy during winter affects the rate at which water is taken up for plant processes. During the freezing months, the sludge application is normally stopped and reeds are harvested. *Phragmites* is considered to be an extremely tolerant plant that can withstand a wide range of

temperatures, the most desirable temperature range being 12 to 23 °C (USEPA 1988). The USEPA estimates that New Jersey facilities experience total annual downtime due to bad weather of only 20 to 30 days (1987). Survey results show that some facilities do not slow down operations during the winter months, while others reduce their sludge application (usually December to March). At one plant, the operator reported that sludge is hauled during the colder winter months, depending on the weather. Note that freezing and thawing of sludge is itself a sludge-dewatering technique (Martel 1988). More research needs to be done as to how effectively reed beds will function in combination with freezing and thawing, especially during the winter months.

Replanting

Survey results revealed that only three facilities reported a need to replant. One facility reported that 50 percent of the reeds initially planted failed to survive. The limited reed survival at this facility was attributed to the excess heat generated in the greenhouse. However, after the removal of several glass panes from the greenhouse and the installation of two fans, the survival rate rose to 90 percent. At another facility, one bed was entirely replanted while three others required partial replanting. The primary causes of the reed die-off in this instance was aphid infestation and summer heat. Another facility reported that their reeds had to be replanted four times before they established properly. This facility's last replanting (Spring 1989) proved to be the most successful. The reed survival at this facility was attributed to a program of watering with an irrigation system, heavy fertilization, and a delay in the application of sludge for several weeks.

The Role of Reed in the Beds

The use of reed beds in sludge dewatering combines the action of conventional sand-drying beds with the effects of reed in a constructed wetland. The plant's great demand for water enables a further sludge desiccation, which results in a residue with a high solids content. For the whole process to be functional, the use of rooted vegetation in the reed bed is a key component. The presence of active plants capable of growing in sludge affects the hydraulic functions of the system, and the associated sediment ecosystem and transformations that occur in the sludges.

The reeds' root system creates a permanent series of channels that drain moisture from the overlying sludge layers. This is partly physical (resulting from the reeds' major and minor root network) and partly microbiological (resulting from the activity in the ecosystem that develops in association with the root system). The reeds possess the ability to transmit oxygen from the leaves to the roots, creating aerobic microsites (adjacent to the roots) in an otherwise anaerobic environment, which assist in the stabilization and mineralization of sludge (USEPA September 1987). Research is needed to compare aerobic sludge to anaerobic sludge in terms of reed growth and chemical characteristics of sludge to explain this process.

The microbial system associated with the reeds, for example, apparently maintains micro-drainage channels near and associated with the root system, clear of the characteristic obstructive films typical of air-dried sludge, which minimizes drainage (Banks and Davis 1983a). The plant activity, in effect, promotes drainage and water absorption by the root system. While some of the water drains freely, an even larger portion is drawn up by the roots to the leaf system to be transpired to the atmosphere. A water mass balance should be constructed to investigate the dewatering capability of reed beds.

Of the facilities studied, eight reported periodic testing of the sludge in the reed beds. Results were only available from one Vermont facility. Testing at this facility was done before a planned premature sludge removal; the sludge was to be removed after only 3 years of applications due to reed die-off and failure. After evacuation, the beds will be replanted. EP Toxicity tests (as of September 1989) indicate

that the sludge fell within the allowable Vermont EP Toxicity levels for all parameters except lead. The calculated EP Toxicity value for lead was 7.66 mg/kg dry weight sludge, as compared with the accepted limit of 2.66 mg/kg. Further research should be done to explain the mass balance of heavy metals that enter the reed bed. In all, more agronomical research would provide a better knowledge and understanding of reed beds.

Other Problems

Most of the facilities reported that the reeds were frequently and severely infested with aphids, especially during the summer months. Eight facilities used a combination of lady bugs and insecticide annually to control infestation, while remaining facilities were using only lady bugs and three using only insecticide. In this study, two facilities (plants O and X) reported no problems with aphids. Some of the plants also needed to weed their beds periodically to eliminate the opportunity for the weeds to stifle growth of the reeds.

Additionally, visits to the facilities with reed beds enclosed in greenhouses indicated that the greenhouse environment generates severe heat and drought stress on the reeds, making it difficult for good reed establishment.

During the field visits, several operators voiced their concern that sludge disposal could become a problem if future regulatory standards prohibit the disposal of sludge in landfills.

Plant Tolerance

Phragmites can normally tolerate a wide range of temperatures, but desirable growth temperatures range from 12 to 23 °C (53-73 °F) (USEPA 1988). The reeds are sensitive to extreme heat and therefore they should be cultivated in an ambient environment.

In addition to temperature variations, *Phragmites* tolerates a variety of environmental conditions, which explains its worldwide distribution. According to estimates, reeds can tolerate a pH range of 2.0 to 8.0 and a maximum salinity of 45 ppt (parts per thousand) (USEPA 1988). *Phragmites* does require a wet, but not a flooded, environment because the plant will not tolerate extended inundations of over two-thirds of the plant height. *Phragmites* will not tolerate shaded conditions (Pompeo 1984). Further research regarding the phytotoxicity of reeds is needed to determine the loading limitations of these beds.

Sludge Residence Volume

Since no plant has sufficient data to complete a recommended 10-year cycle for sludge removal, it is hard to determine long term sludge residue volume. However, many facilities have recently started operation and the operators provided an approximate depth of sludge accumulation at the time of the study. Plants J, L, and B reported sludge accumulations of 51, 46, and 61 cm (20 in./3 yrs, 18 in./1 yr, and 24 in./4 yrs) respectively. Some of the newer plants (R, P, and V) reported sludge accumulations of 41 cm, 46 cm, and 20 cm (16 in./1.5 yrs, 18 in./1 yr, and 8 in./1 yr) respectively to date. However, the depths were estimates for a short time period and do not form a good basis for estimating the long-term sludge residue volume. Another facility in New Jersey reported that the sludge at the bottom of the reed beds was a dark, loamy compost-like substance with an earthy smell. Further scientific research may be needed to thoroughly understand the factors affecting sludge volume reduction on the beds; for example, carbon/nitrogen ratio, micro-organisms' capability to desiccate the sludge, and weathering effect.

Nutrient Balance

Some of the facilities had laboratory analyses performed on their sludge, for nutrients and metal contents. However, they did not provide any quantitative data for our study.

A comparison between the nutrients in sludge versus the nutritional needs of the reeds has not been accurately determined. However, reed growth at various installations was observed to be tall and dense, i.e., in a healthy growth phase. Salinity (Max. 4.5 percent) conditions also affect the reed height and abundance. In addition, *Phragmites* is known to be important in nitrogen recycling (Cooper et al. 1990). The widespread nature of *Phragmites* indicates that, while nutrient levels may affect plant quality, they do not appear to inhibit plant survival. However, more nutrient balance information will help to accurately determine the solids loading criteria.

4 DISCUSSION

Comparison of Reed to Sand-Drying Beds

The most frequently used method to dewater sludge at Army installations is by using conventional sand-drying beds. To adequately assess the potential for using reed beds in this application, a number of elements must be considered, the most important of which are performance, economics, and reliability. Table 6 shows a comparison of sand-drying beds and reed beds.

Solids Loading Rates

The loading rate will be decreased when weather conditions are not favorable to sludge drying on the sand-drying beds. When sand media is clogged, the solids loading rate will be substantially decreased because drying is only possible through evaporation. Table 6 shows the actual solids loading rates for the reed beds as obtained from the survey. This data shows that anaerobic sludge loading rate is lower than aerobic sludge loading. Although a comparison between the sand-drying bed's maximum loading rate and the reed bed's actual loading rate will not give an accurate measured comparison of the two methods, the figures suggest that well-maintained sand-drying beds will likely dewater more sludge than reed beds of the same area. However, as yet there is no data specifying an allowable maximum loading for the reed beds while the growth of reeds is not hampered.

Table 6

Comparison of Reed to Sand-Drying Beds

Parameter	Reed Bed	Sand-Drying Bed
Solids Loading Rate (lb/sq ft/yr)	Solids loading rate of anaerobic digested sludge ranged from 2-12 lb/sq ft/yr (9 to 59 kg/m ² /yr) and that of aerobic stabilized sludge ranged from 2.3-21.7 lb/sq ft/yr. The average solids loading rate of anaerobic digested sludge is 4.7 lb/sq ft/yr and aerobic stabilized sludge is 10.9 lb/sq ft/yr.	Primary plus waste activated solids loading rate for uncovered beds: 15 lb/sq ft/yr (USEPA, September 1979). Digested primary plus waste activated sludge for uncovered beds: 12-20 lb/sq ft/yr and these can be increased to 17-28 lb/sq ft/yr for covered beds (USEPA, 1987).
Cost of Construction/Conversion and Start-up	Estimates for retrofit from the facilities ranged from \$0.42 to \$9.22/sq ft. At Fort Campbell, the cost of retrofit was about \$2/sq ft. For the new construction of reed beds, the capital cost ranged from \$9.22/sq ft to \$25/sq ft. Most of the facilities were converted from existing sand-drying beds. The incurred cost of retrofit included acquisition of reeds and planting, addition of freeboard on the beds for sludge accumulation, and any other retrofitting (e.g., filter media, under drain, etc.).	Appurtenant equipment includes sludge feed lines, pumps and front end loaders/dump trucks for removal (<2MGD). Based on % of solids generated, and annual sludge volume, base capital costs are (at annual sludge volume 5 Mgal/yr): 2% solids, 15 lb/sq ft/yr \$262,000; 4% solids, 22 lb/sq ft/yr \$333,000; 6% solids, 28 lb/sq ft/yr \$405,000 (USEPA September, 1979). All values shown are present values updated to May 1992.

Table 6 (Cont'd)

Parameter	Reed Bed	Sand-Drying Bed
Operation and Maintenance	Daily or bimonthly sludge loading requires monitoring for suitable amount. Harvesting occurs during late fall to winter, and requires between 1-3 days of work depending upon the size of the reed beds. No heavy and mechanical equipment is used. Hedge clippers, sickles, and "weed wackers" are used. The harvest is disposed of by hauling to landfills, composting, or burning. There is no need to remove dried sludge layers. Twenty facilities reported that they have from 48 years remaining before the reed beds are entirely evacuated for new planting. However, the facilities were advised to cease sludge application 6 months prior to evacuation. Annual maintenance occurs during harvesting/weeding and ranges from 1-3 days; and labor requirement ranges from 1-3 persons.	Dewatered sludge is hauled off site to either landfills or dedicated disposal sites. Most often dried sludge is removed manually and transported to disposal sites by trucks. Sludge disposal costs at landfill range from \$60-\$70/yd (field data in Pennsylvania, plant U). However, the landfilling cost depends primarily on the geographical location of the disposal site. When the solids content reaches between 18-60% (dependent on the type of sludge), sludge is removed from the beds and a fresh cycle of sludge application is started. Annual maintenance estimates man-hours expended per bed area: 1000 sq ft, 400 hr/yr; 5,000 sq ft, 580 hr/yr; 10,000 sq ft, 720 hr/yr; 50,000 sq ft, 2,210 hr/yr; 100,000 sq ft, 4,400 hrs/yr (USEPA, September 1979). The top layer of the sand-drying bed is often replaced with new sand to enhance drainage.
Winter Conditions	During winter the reeds enter a dormant phase. Several facilities reported that they do not limit application during the winter. Others either lessened the amount of sludge applied, or ceased application during freezing weather to harvest reeds.	Sand-drying beds are not operative during winter months because of low drying efficiency. Therefore, storage of 4 months during winter period is often required.
Sludge Residue Volume	None of the facilities have reached the recommended 10-year time limit for evacuation and complete removal of the sludge. Therefore, the sludge residue volume cannot be determined. Plant operators reported an approximate depth of 8-18 in. of sludge accumulation per year.	Sludge is applied in layers between 8 and 12 in. deep. Once sludge is dewatered to between 18-60%, the sludge cake is removed. Bed areas depend upon factors such as availability of land space and type of sludge. Sludge cake is often disposed of at landfills.
Type of Sludge	Higher volume of aerobic sludge can be dewatered than that of anaerobic sludge.	All types of sludges can be applied.

Construction Costs

Since most Army installations use sand-drying beds, the retrofit to reed beds is economically feasible. Reed beds are usually retrofitted from existing sand-drying beds. The major fraction of the cost is associated with acquiring and planting the reeds and adding freeboard on the side wall. Reed planting cost will likely decrease due to economics of scale when more Army sand-drying beds are retrofitted to reed beds.

Labor

Unlike sand beds, reed beds are not labor intensive because the dewatered sludge is not removed regularly. Since none of the facilities under study had reached their recommended 10-year cycle, the labor needed for the final sludge removal could not be determined. However, most of the required labor

associated with reed bed operation is expended during the annual harvesting and weeding. The final cleaning costs will include removal of entire sludge residue, reeds, and sand.

Seasonal Limitations

Like the sand-drying beds, reed beds can be operated even during cold weather, as long as the ground is not frozen. Dewatering due to plant activities will decrease as the reeds become dormant. During the winter months, when the weather is severe or frozen conditions exist, many reed bed facilities decrease the rate of sludge application. In warmer areas, sludge application is unaffected. However, winter operation may possibly use a freeze-and-thaw technique (Martel 1988).

Use of Stabilized Sludge

The application of raw or primary sludge is not recommended for reed beds. Most of the reed bed facilities under study have applied secondary or digested (essentially stabilized) sludge. The sludge did not require conditioning, a process step in wedgewater or vacuum-assisted beds. Most of the facilities reported that the sludge was gravity fed to the reed beds, eliminating the power requirement to pump the sludge to the beds.

Advantages

- Reed beds do not require sludge removal at every dewatering cycle. With the exception of initial reed establishment and the evacuation process at every 10 years, the only routine operation required is annual harvesting and possibly some infrequent weeding. Hauling and disposal costs are extremely low. Annual hauling is required for the reed harvest only if the plants are not composted onsite. Sludge disposal has not yet been performed on any facility studied. The facilities should complete the recommended 10-year cycle before evacuating sludge from the beds.
- Existing sand drying beds can easily be converted to reed beds with only a small investment.
- Reed beds, in addition to offering the supply of normal dewatering properties of conventional sand beds, have the added benefit of a growing plant, which additionally dewateres the sludge through the normal plant processes. The rhizome and the roots penetrate the sludge layers and due to their mechanical action, keep pathways for dewatering clear. Moreover, the reed roots can take up a quantity of water through evapotranspiration, which is double the normal surface water evaporation (Cooper et al. 1990, p 260).
- No sludge transportation and disposal costs are incurred until the bed is evacuated.

Disadvantages

- While reed beds may be used on a limited basis a short time after planting, a minimum of 3 months to 2 years may be required before the reeds can be fully functional and established.
- Some states require permits to operate reed beds, e.g., New Jersey and Massachusetts. In southern states where the ground does not freeze, to permit efficient harvesting, reeds are generally burned. This operation also requires permits. In the future, open burning may not be allowed.

- Septic or primary sludge seems to overwhelm the reeds. There is little success with this type of sludge being applied to the beds.
- Reed beds are best suited for small facilities due to low loading rates, amount of bed space required, and the annual need to harvest.
- Reeds cannot assist the dewatering process during winter when the plants are dormant.
- The actual maximum period of operation and scientific loading criteria are not available. At the time of this study, the oldest reed bed had a successful operating history of 8 years. Continued monitoring of reed bed performance is planned throughout at least the 10-year cycle.
- Aphid infestation could wipe out the reeds, necessitating replanting and starting over. (This actually occurred in Pennsylvania in 1989.) Most facilities were able to use biological controls, but some others had to spray insecticides. Extreme heat, as occurs in greenhouses, can be detrimental to reed growth. However, these control measures are required only during the initial stages of reed growth when the reed plants are most vulnerable to aphid attacks. Once the reeds are fully developed, this operation is no longer needed.

Potential Use

Most of the surveyed WWTPs were successful at overall sludge dewatering, meeting operation and maintenance requirements, and in their general performance. Currently, plants have been operated for up to 8 years without any major problems. Moreover, the results have been encouraging as to the application of this simple and economical technology to Army installations. In the private sector, the number of wastewater treatment plants using reed beds has doubled in the past 3 years. Further research is planned to refine this promising technology.

5 CONCLUSIONS

A background investigation showed that reed bed dewatering technology has relatively broad application in drying wastewater, dredged spoils, and sludge. In reed beds, the dewatering process takes place by three mechanisms: evaporation, drainage, and evapotranspiration. The root and rhizome system of the common reed *Phragmites* promotes drainage by maintaining drainage channels through the sludge volume, and also by actively drawing water out of the sludge into the plant, from where the water is free to evaporate through the leaves of reed. This process complements surface evaporation, which can be slowed by formation of obstructive films common to air-dried sludge.

Reed beds require less labor than sand, vacuum-assisted, or wedgewater beds, essentially by eliminating the labor required for regular sludge removal. Functioning reed beds have operated continuously for more than 8 years without removing sludge; in fact, it is estimated that sludge residue need not be removed from the reed bed for 10 years from the start of application. This eliminates the need to dispose of a large volume of sludge at a landfill regularly, even though reeds must be harvested and removed annually. Average solids loading rates on reed beds are comparable to those of sand-drying beds. However, there is a wide range of loadings for reed beds.

Construction and implementation of a new reed bed system is costly because of the initial construction cost of sand beds. However, it is a relatively simple process to retrofit reed beds to existing sand-drying beds. The main costs for retrofitting reed beds to existing sand-drying beds is for acquiring and planting the reeds.

Reed beds do not require the applied sludge to be conditioned to be effectively dewatered. Vacuum-assisted beds or wedgewater beds incur additional conditioning costs since well conditioned and sludge dewaterers best.

It is concluded that reed bed dewatering technology has a good potential for dewatering sludge generated at U.S. Army WWTPs mainly because the Army has many existing sand-drying beds. The lower loading rate and larger area requirement of reed beds as compared with sand-drying beds, and the need to harvest the reeds annually, may make the reed bed technology infeasible for large WWTPs.

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APPENDIX: Sample Questionnaire

REED BED TECHNOLOGY QUESTIONNAIRE

Name of the facility: _____

Mailing address: _____

Telephone Number: _____

Plant Manager's name: _____

1.0 DESIGN:

- (1) What is the waste water inflow rate at your plant ?
_____ (gallons/day).
- (2) Under normal operating conditions what is the sludge loading rate ? (example, gal/bed, gal/sq ft) _____
What is this rate in approximate layer depth ? _____ inches.
% solids ranging from _____ % to _____ %
What is the frequency of application? _____
_____ (time per year).
- (3) How many beds do you have and what is the total area ? _____

What is the size of an individual bed ? (example, 50ft * 100ft)

- (4) What type of treatment unit do you have ? Check any
Primary: _____ Secondary: _____ Thickening: _____
Digested: (1) Anaerobic _____ (2) Aerobic _____
Others please specify _____

2.0 CONSTRUCTION DATA:

- (1) Are your beds 1) New _____ 2) Retrofitted from sand drying beds ? _____
- (2) Construction costs: \$ _____/sq.ft.

3.0 OPERATION AND MAINTAINENCE:

- (1) Operations/personnel/labor
How many man-hours are required for the reed bed operation and maintenance ? _____/year.
- (2) If there was on-site dewatering previously, provide cost of hauling/disposal of sludge in \$ _____/year.
- (3) Annual operation and maintenance costs: \$ _____.

- (4) Do you have any specific maintenance requirements (e.g. weeding, aphid control, etc.) Yes _____ No _____
If yes, please describe them _____

4.0 REED BED PERFORMANCE:

- (1) How do you determine the resting period before the next loading ? _____
- (2) Is the sludge application limited by the winter season ? _____
If yes what is the average length of time that the sludge cannot be applied ? _____.
- (3) What is the average rate of residue accumulation at your beds? (e.g., inches/year) _____
- (4) Was any additional planting necessary after the first planting ? Yes _____ No _____. What was the reed's height at the first application ? _____ feet/inches.
- (5) How much time elapsed after planting until sludge was first applied ? _____.

5.0 HARVESTING OF REEDS:

- (1) Are the Phragmites harvested annually ? Yes _____ No _____
What is the volume of harvested reeds ? _____ cu.feet.
- (2) What procedure and equipment is used in harvesting ? _____
- (3) At what time of the year is harvesting carried out ? _____.
- (4) Describe how the reeds are ultimately disposed of ? _____
- (5) What is the cost of disposal ? \$ _____/year.
- (6) Is any type of test performed on the harvested reeds ?
Yes _____ No _____. If yes please explain _____.

6.0 CLEANING AND REPLANTING REED BEDS:

If you have cleaned and/or replanted the entire beds, answer the following.

- (1) What equipment is used in cleaning the reed beds ? _____

- (2) How many years elapsed since first planting to clean and replant reeds ? _____.
- (3) How much sludge can be applied to a reed bed before it must be cleaned ? _____ inches/feet.
- (4) Are any tests being conducted on the sludge? Yes____ No____.
If yes please describe the results. _____

- (5) How do you dispose of the residue ? _____
_____.
- (6) Was the residue hazardous by definition ? _____

7.0 GENERAL

- (1) Are you pleased with the performance of the reed bed system ?

- (2) Did you have any problems in the past or do you foresee any within the future ? Please explain _____

_____ ***** _____

NOTE: The following space is provided should you wish to provide additional comments and/or information which you feel would be useful for our study .

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Nat'l Institute of Standards & Tech

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